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Review

Ecological floating bed (EFB) for decontamination of polluted water bodies: Design, mechanism and performance

Kundan Samal*, Soham Kar, Shivanshi Trivedi

School of Civil Engineering, Kalinga Institute of Industrial Technology-Deemed to be University Bhubaneswar, 751024, Odisha, India

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ABSTRACT

Worldwide water quality is degrading and most of the water bodies are now being contaminated by heavy load of pollutants from various industries. Aquatic ecosystems are also disrupted affecting various flora and fauna adversely. Water bodies dominated with aquatic plants have high yielding capacity. These plants are capable of high nutrient accumulation and creating favorable condition in rhizosphere for microbial organic degradation, which can be applied in the restoration process of polluted lakes, natural streams and wetlands, etc. Ecological Floating Bed (EFB) is designed by using aquatic plants, floating like mat on the surface of water. The plant roots hang beneath the floating mat and provide a large surface area for biofilm growth. This paper reviewed the EFB concept, structure, mechanisms and functions. Screening of suitable macrophyte species, involvement of biofilm in organic removal process and necessity of growth media have been discussed briefly. Apart from this, effect of depth, buoyancy, vegetation coverage ratio are also represented. Detail mechanisms of oxygen transfer from top to bottom of water biomass have been well analyzed. Various pollutants present in wastewater like organics, solids, nitrogen, phosphorous, heavy metals etc. and their removal mechanism have also mentioned. Again biomass needs to be harvested in regular interval, else the absorbed nutrients may re-enter to the water body. Overall, EFB is an efficient and effective wastewater treatment technology and further research is necessary for its better utilization. Finally, based on reviews, recommendations have been made for future research.

1. Introduction

Exponential growth of population, rapid urbanization and quick industrialization has already put pressure on freshwater supply. At the same time it is being a starring problem to manage the generation of wastewater and its treatment. According to Slutsky and Yen (1997), worldwide precipitation rate recorded every year is 119,000 km^3, among which 61% evaporates and 39% flows as storm water runoff. Gradually the runoff quantity is increasing day by day due to rise in impermeable surfaces (roads, roofs, etc.), which obstructs flow of rainwater into the ground. During heavy rainfall, storm water runoff carries all types of pollutant load on land into aquatic and terrestrial ecosystems, which makes the water body polluted and toxic (Chang et al., 2013; Samal et al., 2017). In urban areas motor vehicle emissions, vehicle tire wear, crankcase oil drips, particles from asphalt road surfaces, heavy metals, poly-cyclic aromatic hydrocarbons (PAH) from roads are washed into rivers, lakes, ocean increasing the toxicity of sediments and water. Effluents from various industries like pharmaceutical, metallic, textile, oil, paint, chemical, etc, are also discharged into aquatic ecosystems without proper treatment (Chen et al., 2012; Hwang et al., 2016; Schwammberger et al., 2017). Most of the pollutants are persistent in nature and are transferred from one organism to other in aquatic ecosystem through food chain.

In developing countries, 80% of sewage is released to water bodies without prior treatment, resulting in nutrient and organics concentration increases. Apart from this, fertilizer and pesticides from cultivation land are also washed into rivers, lowland lakes and reservoirs (Ning et al., 2014; Samal et al., 2018). Surplus amount of nitrogen and phosphorous in freshwater leads to undue growth of phytoplankton species in lakes, a process called eutrophication (Zhao et al., 2012, 2016). There are two ways of preventing water pollution, i.e. either forbid pollutants entering water body or remove the existing pollutants (Chua et al., 2012). Authorities from worldwide have already started to focus on prevention process which can restitute the polluted water body and protect biodiversity and a number of strategies are being implemented to remove the pollutants from water bodies like bio-manipulation, removal of sediments, re-oxygenation and use of ecological floating bed, etc. (Nayak et al., 2018; Song et al., 2014; Yeh et al., 2015). Apart from this other biological process like septic tank, fixed-activated sludge treatment, recirculating sand filter, trickling filter,

* Corresponding author.
E-mail address: kundan.samalfce@kiit.ac.in (K. Samal).

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rotating biological contactor, macrophyte filter, vermifilter, oxidation pond, aerated lagoon are available to treat various domestic as well as industrial wastewater. Several operational problem occurred in the above processes like sludge generation, clogging, lengthy start up time, energy requirement, odour generation, effluent pH imbalance, etc. Most of these problems can be avoided by using EFB for treatment of wastewater. In other way, it is quite impossible to treat a polluted water body by passing through any kind of filter and chemical treatment methods also cannot be adapted as it may kill aquatic organisms, destroying their ecosystem. The treatment system should only purify the polluted water without disturbing the aquatic life and their habitat. For this reason, EFB is a better option to decontaminate the contaminated water body.

Ecological floating bed (EFBs) is an economical and sustainable green technology to restore polluted lake water. It is based on nature's self-cleaning capacity and no toxic byproduct is generated during treatment process. The removal efficiency of pollutants in EFB systems are often influenced by structure, aeration level, temperature, pollutant contents in the wastewater (Headley and Tanner, 2012). Hydrophytes have a fundamental role in the structure and functioning of aquatic ecosystems, therefore used in EFB for the purification of wastewater owing to their efficiency in accumulating nitrogen and phosphorous and preparing suitable condition for biodegradation of organics trapped by roots and rhizomes (Samal et al., 2018; Di Luca et al., 2011). Recently various effort are being made for rapid removal of pollutants from water bodies using EFB. Thiosulfate-driven denitrification are being implemented to enhance nitrogen removal (Gao et al., 2018). Phosphate accumulating microorganisms (PAM) are inoculated in the water body to accelerate phosphorous removal (Bi et al., 2019). Artificial light weight bio-carriers are being used to provide more buoyant force to the floating bed as well as surface area for attachment of microbes (Luca et al., 2019). Research are also being focused to develop genetically modified floating macrophyte for rapid intake of heavy metals and nutrients from water. Current review focused on application of EFB for polluted water body treatment and their various design, and operation parameters. It also covers the detail mechanisms of organic degradation, nutrients removal, harvesting and management of hydrophytes.

2. Classification of constructed wetland

Constructed wetlands (CWs) are engineered system utilizing different plant species and bed materials to treat different types of industrial effluents, sewage and polluted water. The system is based on advanced natural process/technology. The classification is based on water flow regime and types of macrophytes used (Fig. 1). In surface flow (SF) wetland, wastewater flows over bed materials and sunlight may reach to the bottom of the system. In subsurface flow (SSF) wetland, wastewater flow is maintained below the bed materials. Pollutants present in the wastewater come in contact with bed materials, gets attached to the biofilm and later degraded aerobically (Samal et al., 2018; Vymazal, 2007). When the wastewater is fed at the inlet and it flows horizontally through the bed to the outlet, then it is called horizontal flow (HF) wetland. In case of vertical flow (VF) wetland, wastewater drains vertically through the bed either up or down. VF wetland promotes nitrification as atmospheric oxygen gets transferred to the bed through water suction and HF wetland promotes denitrification due to limited oxygen supply. Hence the efficiency of nitrification and denitrification depends on the operating conditions of wetlands. Combination of VF and HF wetland system known as hybrid wetland, effectively removes nitrogen from wastewater (Gao et al., 2018; Olguín et al., 2017; Samal et al., 2017). Based on plant species, wetlands are further classified into different categories as shown in Table S1. In these systems, biomass and roots play a major role in pollutant removal process. Aerial tissues, under water tissues and root systems optimize the performance of wetland (Zhang et al., 2017). The present paper deals only with freely floating macrophyte system which is termed as ecological floating bed (EFB).

3. Design of ecological floating bed

Ecological floating bed utilizes emergent plants growing as a floating mat supported over a floating frame in the water rather than rooted in the sediments. The roots are extended into the water to uptake dissolved pollutants (Schneider and Rubio, 1999) while the plants stem remains above the water level. Beneath the floating mat, a hanging network of roots, rhizomes and attached biofilms are formed, which provides a biologically active surface area for biochemical as well as physical processes such as filtering and entrapment (Bi et al., 2019). Fig. 2 shows a schematic diagram of an ecological floating bed (EFB). While designing an ecological floating bed (EFB) emphasis should be given to suitable macrophyte species selection, installing proper buoyant materials, maintaining required water depth and shading, etc. The details of each factors has been discussed below.

3.1. Macrophytes

Screening the suitable macrophytes for the design of EFB is a critical task. As the plants need to float on water surface, the chosen species must have high quantity of aerenchyma tissues. The plant should be native, aesthetically pleasant, non-invasive and perennial species sustaining in the aquatic environment. The plants used in EFB acts as an insulation layer during winter. High amount of nutrient uptake is a mandate criterion for EFB species (Waajen et al., 2016; Williams et al., 2002). The root system in these plants reduces water velocity thereby increasing sedimentation process (Bankston et al., 2002). They release oxygen into the water body and enhance aerobic degradation of pollutants. Nutrients present in wastewater are consumed by the plant species and stored in their tissues. There are some other invasive macrophytes having high amount of nutrient uptake capacity, but their negative impacts on aquatic ecosystem suppress their benefits. Different species have different wastewater treatment capacities owing to their growth rate, root type and accumulation capacity (Samal et al., 2017; Zhu et al., 2011).

Most of the studies in EFB concentrated on herbaceous species with focus on aquatic plants. Terrestrial species can be used in EFB as they are naturally fast growing with higher biomass. *Canna, Typha, Cyperus, Lollium, Chrysopogon* species are most commonly used plants in EFB globally. Li et al. (2010) treated lake water in a mesocosm study by using *Ipomoea aquatica* species and the observed TN, TP efficiency were 66.4–76.5% and 45.7–61.7% respectively. Weragoda et al. (2012) planted *Typha angustifolia* in a floating bed wetland for the treatment of domestic wastewater and reported BOD removal by 48.5–76.1%. Sun et al. (2009) observed 100% NH_4 removal and 50.4% TN removal in treatment of river water using *Canna* species. During a batch study conducted by Yang et al. (2008) for the treatment of nutrient solution planting *Oenanthe javanica*, 17–43% COD and 31–64% TN removal was obtained. Different researchers have utilized different plant species and currently research needs to be focused on various design aspects of EFB to enhance the treatment process as well as increase the symbiotic relationship between plants and microorganisms under water.

3.2. Biofilm

Biofilms are communities of microorganisms (bacteria, fungi, algae) that get attached to each other and to stable surfaces. It consists of cells and extra cellular matrix produced by cells, also well known as extracellular polymeric substances (EPS) (Chan et al., 2008). They provide mechanical stability, enhance water retention, improve nutrient sorption, give protection against viruses and possess antimicrobial activity (Jasper et al., 2013). The common biopolymers are polysaccharides, proteins and nucleic acid, which are/is processed by extracellular

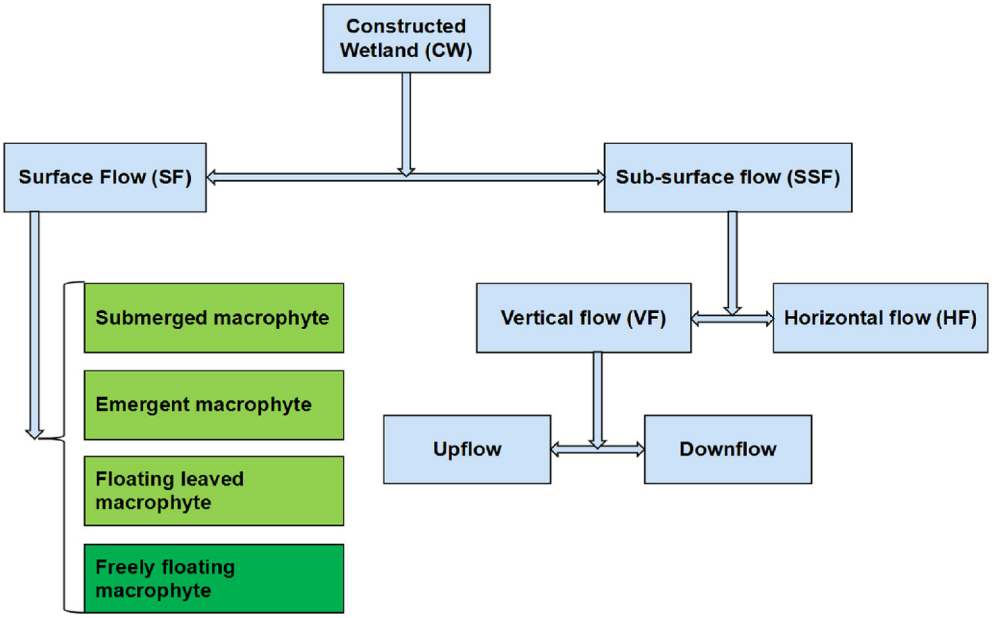


Fig. 1. Constructed Wetland (CW) classification based on wastewater flow and macrophyte species.

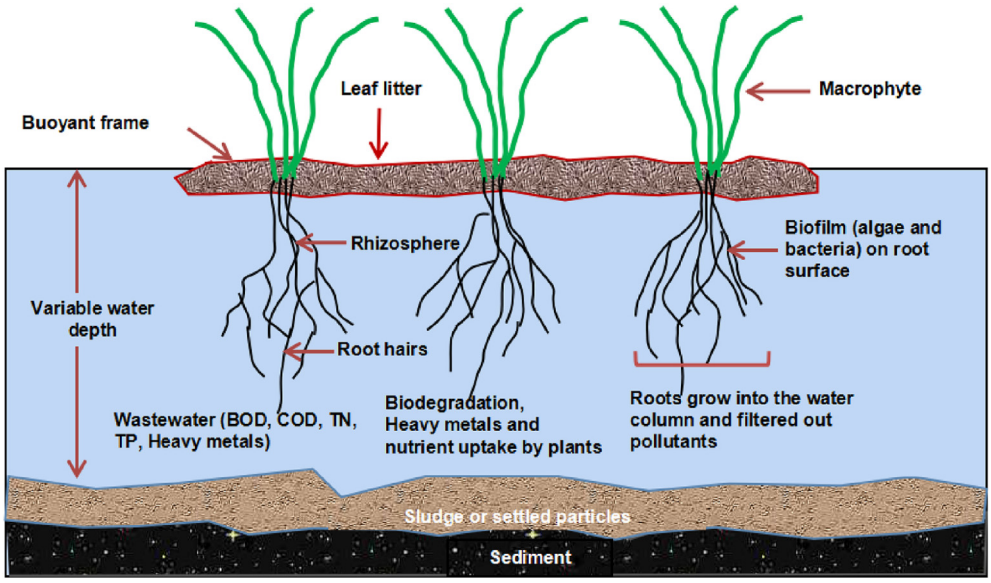


Fig. 2. Schematic diagram of an ecological floating bed (EFB).

enzymes to form EPS (Darajeh et al., 2016). Granulan, alginate like exopolysaccharide (ALE), acid soluble polysugars and glycosylated proteins are common EPS found in wastewater treatment plant. Biofilms are slimy and sticky in nature which entraps suspended solids present in wastewater (Färm, 2002; Meuleman et al., 2002).

In order to increase underwater surface area in EFB, artificial biofilm carriers are used so that biofilm biomass increases along with filter efficiency. According to Xiao and Chu (2015), biofilm carriers have higher specific surface area (3000–7000 m^2/m^3) than plant roots (7–114 m^2/m^3), which helps in equalization of flow fluctuation and pollutants entrapment. Zhang et al. (2016) reported that diversity of microorganisms is higher in biofilm generated in biological surface than artificial biofilm carriers. The bacterial abundance in biofilm depends upon pollutants concentration, metabolic activities, root growth and root exudates. Overall, presence of microbes in floating bed enhances the treatment process. Stewart et al. (2008) treated municipal wastewater in floating bed without plant species and concluded that removal efficiency of ammonium and nitrate were higher in floating bed with microbes than without microbes. Sun et al. (2009) confirmed that there is an increased nitrogen removal after adding immobilized denitrifier in floating bed.

3.3. Growth media

Selection of appropriate media is an essential step towards designing a sustainable floating bed for the treatment of wastewater. Growth media should contain enough pore space to allow exchange of air so that aerobic condition is maintained. Media sometimes affect the buoyancy adversely when it absorbs more water. While choosing the growth media, factors as porosity, water retention, capillarity and fertility needs to be considered (Brisson and Chazarenc, 2009; Tanner and Headley, 2011). Coarse peat, soil, coconut fiber, bamboo, compost, charcoal, etc have been used as growth media in floating bed (Panigatti and Maine, 2003). Coarse peat-moss or coconut fiber amended with

small amount of compost may provide a suitable basis for floating growth media. Addition of vermiculite or pumice may act as beneficial light-weight bulking materials providing additional air space without significantly increasing the weight of the mix (Borne, 2014). The materials used in growth medium should not affect the pH of water. Cao and Zhang (2014) investigated on TN and NH_4 removal in floating bed planted with *Canna* sp and *Calamus* sp using rice straw and plastic fillings as substrates and without any substrates (control). The bed with rice straw removes more TN than plastic fillings and control. Overall, while choosing growth media different aspects should be considered like, its impact on water body, impact on microbial diversity, own biodegradability, leaching capacity, etc.

3.4. Depth

A water depth of 0.8–1.0 m needs to be maintained for the steady functioning of floating bed wetland. If the depth maintained is less than the above values, roots of macrophytes extended to sediment and attached. In case the water level increases in the floating bed, there is a chance that roots may not be able to get detached from the benthic zone and macrophyte may submerged in the water body (Ayaz and Saygin, 1996). It leads to death of the plants causing significant damage to the floating bed. Length of macrophyte root varies from species to species. Growth of the root affects the above ground biomass too. Depth needs to be retained considering the kind of macrophyte species planted in water (Chan et al., 2008; Kyambadde et al., 2004). It is necessary that the roots should be in floating condition in the wastewater.

3.5. Buoyancy

In Ecological floating bed, buoyancy is naturally kept up as a result of air retained in the spongy roots and rhizomes. Again due to the anaerobic decomposition in the sediment, CH_4 gas is generated in the bottom and gets trapped in the root mat, which keeps the macrophyte in floating form on the surface of water (Garbutt, 2004; Lynch et al., 2015; Sun et al., 2005). The above two processes regulate the buoyancy of a particular plant species, depending upon the age of the plant, growth phase and gas generation rate. The processes contributing to mat buoyancy is more active in summer than in any other season due to high temperature which increases the metabolic activity of the plant and microbes (Bu and Xu, 2013; Sheng et al., 2013).

An inexpensive and simple material should be used which can be removed or decomposed once the floating bed is grown and established. The most used materials to achieve flotation are sealed PVC or PP pipes, polystyrene sheets, bamboo, inflatable vinyl pillows, etc (Table 1). In artificially designed floating bed, a floating structure or raft may be necessary to provide flotation during the initial time to facilitate the macrophyte establishment until auto-buoyancy is achieved. The floating raft consist of a buoyant frame in which macrophyte is/are planted (Xian et al., 2010; Yeh et al., 2015). A floating frame is constructed using sealed length of plastic pipes and these may be joined together to form a buoyant square or rectangular frame. There are also systems with other configurations, in which a rigid frame is not used but elements such as reused PET bottles are used to provide the necessary buoyancy (Basílico et al., 2016).

Kerr-Upal et al. (2000) reported about the design of raft from iron and timber supported by sealed plastic float tanks or styrofoam. Hubbard et al. (2004) constructed a floating platform using PVC pipe, chicken wire mesh and fibrous matting material. Van Acker et al. (2005) reported about a system consisting of thick coconut fiber mats supported by polyethylene nets and polystyrene foam. In India floating rafts are constructed using bamboo interwoven with mats of natural fiber. Bamboo contains a lot of sealed chambers full of air, which are naturally buoyant and it degrades after several years. According to Seo et al. (2013) buoyant material needs to be hydrophobic so that it enhances bacterial adhesion process.

3.6. Vegetation coverage ratio and shading

Vegetation coverage ratio in EFB is an essential factor for water treatment as it regulates the atmospheric oxygen diffusion in the water body. High vegetation cover (more than 50%) may create anoxic condition in the water as it prevents diffusion of oxygen from air to water due to wind activity, whereas low coverage (9–18%) may add insignificant amount of treatment effect (Zhou and Wang, 2010). So, EFB covered with more vegetation has lower DO amount in water than the floating bed without coverage. When the water body is covered by vegetation, sun light cannot pass through the water and photosynthetic algal species starts to decline. Non photosynthetic bacteria starts to predominate in the biofilm developed on the surface of root (Headley and Tanner, 2012). Decomposition of organic matter consume the remaining DO present in water body. Moreover, vegetation coverage has significant impact on pollutants removal. Some researchers have reported that vegetation ratio more than 50% reduce treatment efficiency. Winston et al. (2013) reported 48% TN removal when vegetation coverage is 9%, but the efficiency increased to 88% when the coverage ratio increased to 18%. Chang et al. (2013) found 14% TP removal with 9% coverage. 100% coverage may be considered if the targeted process is denitrification for nitrate removal.

4. Oxygen transfer mechanism

Wetland plant converts into biomass by accumulating inorganic carbon from atmospheric carbon dioxide. The plant stem consist of plenty of aerenchyma tissues or gas assembly, which accelerates oxygen transfer to below ground biomass. Some amount of oxygen is used for plant respiration and some amount releases to outer environment of roots, which affect the biogeochemical cycle (Armstrong et al., 2000). Aerenchyma tissue content varies from 60 to 70% of the total tissue volume present in different plants. Due to respiratory demands of buried tissues, internal oxygen moves down the plant and also supplies the rhizosphere with oxygen. The rate of release of oxygen depends

Table 1
Various materials used to achieve buoyancy during design of EFB.

Sl. No.	Floating frame	Raft area (m^2)	References
1	BioHeaven patent material	0.36	Tanner and Headley (2011)
2	Sheets made of foam	2.00	Yang et al. (2008)
3	PVC pipe (Dia 38 mm), Plastic mesh	0.29	Wang and Sample (2014)
4	Polyethylene material	0.025	Wen and Recknagel (2002)
5	High Density Polyethylene	0.20	Xian et al. (2010)
6	PVC pipes (Dia 1.1 cm) or Bamboos (Dia 1.0–1.5 cm)	–	Zhao et al. (2012)
7	Tech-IA patent material	0.45	Stefani et al. (2011)
8	Polyethylene terephthalate (PET) material (Recycled)	50.0	Borne et al. (2013)
9	Iron and timber	–	Kerr-Upal et al. (2000)
10	Polypropylane copolymer plate and plastic bottles	2.0	Li et al. (2010)

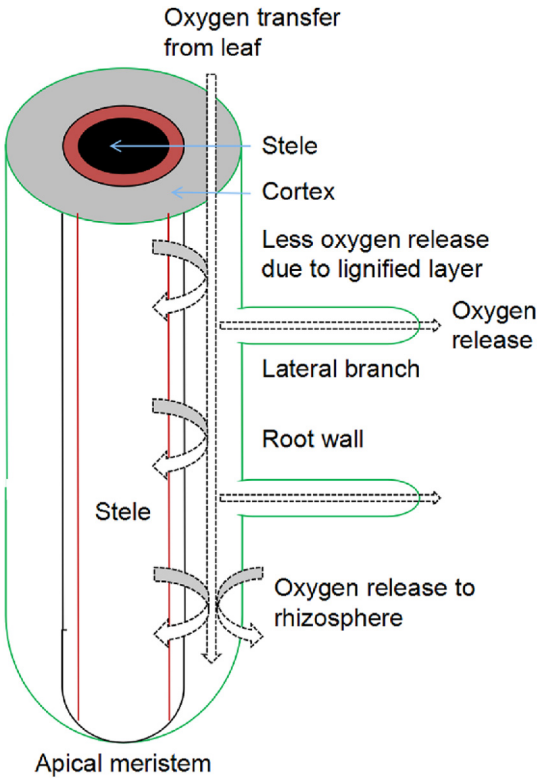


Fig. 3. Pathway of oxygen transfer in a wetland macrophyte root.

upon the inside oxygen concentration, demand of oxygen in rhizosphere, root wall permeability, etc (Armstrong and Beckett, 1987; Brix and Sorrell, 1996). Fig. 3 shows pathway of oxygen transfer in a wetland macrophyte root. The tip of the main root is called apical meristem. It is found at the tip of the shoot and the root, which is a region of actively dividing cells. It causes the plant to grow up and down to get longer. Apical meristem pushes its roots deep below the ground to seek water and anchor the plant. Cells in the apical meristem are permeable and easily exchange gases between surrounding and tissues. The middle portion of the root is called stele and surrounded by cortex which transports materials into the stele through diffusion and stores food in the form of starch. It is typically made up of aerenchyma tissues and surrounded by hypodermis. In older roots and rhizomes, oxygen leakage is less due to the presence of lignified layer in hypodermis as well as cortex. It stops radial leakage of oxygen and facilitates the oxygen flow towards apical meristem through which gas is released. The leakage is highest in apical region of the root and as the distance from the root-apex increases, leakage amount decreases. Rate of release of oxygen is higher in lateral branch also due to less lignified layer and meristematic tissue. Armstrong et al. (2000) proved the same in an experiment using *Phragmites australis* root of length 110 mm long (Fig. 4). The toxic substances are detoxified and oxidized in the rhizosphere (Brix et al., 1992).

Transport of oxygen within the wetland macrophyte takes place by convective flow and passive molecular diffusion of air. In convection process, tissues in the roots are being aerated by throughflow or non-throughflow of air and this is initiated by various physical processes (Armstrong and Beckett, 1987; Winkel et al., 2011). When the process is impelled by temperature difference between the inside plant tissue and the surrounding air, it is called thermoosmosis or thermal transpiration and, if driven by water vapour pressure differences, then it is called humidity induced pressurization (Calhoun and King, 1997). Due to gradient in wind velocity, air also passes through the plant tissues called venture induced convection (Fan et al., 1992; Kirk, 2003; Sorrell, 1999).

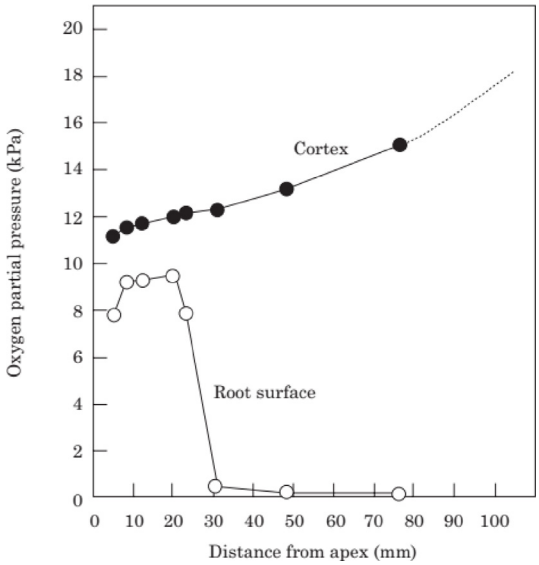


Fig. 4. Oxygen release profile on the root surface of *Phragmites australis* (Armstrong et al., 2000).

Each plant has different types and combination of gas transfer mechanism. Convection is due to generation of pressure gradient between the roots and leave surface, which causes gas to transfer through the entire stem to below ground biomass. In diffusion process, gases are transferred along the stem towards the root (from higher partial pressure to lower partial pressure) due to random molecular movement. The process completely rely upon temperature, gas molecular weight and medium. Diffusive transfer of matter can be mathematically expressed by Fick's law (Brix and Sorrell, 1996; Groot et al., 2005).

5. Pollutants removal mechanisms

5.1. Organics and suspended solids

Organic matter and suspended solids are related to each other and also their removal processes. Organic substances may be biodegradable or non-biodegradable in nature. Dissolve organic substances present in the wastewater maybe directly up taken by the plant roots. Hanging root system from the macrophyte creates a network or mat like structure in the water body. Oxygen from the leaves get transferred to roots and is released from the young root and rhizomes, which supports the growth of aerobic microbes and nitrifiers (Abed et al., 2017; Billore et al., 2009; Samal et al., 2018). Root surface provides the surface area for microbial colonization and repeated proliferation of attached fungi and bacteria slowly increases the biomass amount known as biofilm. Roots also releases some sugars and vitamins such as riboflavin, thiamine, pyridoxine, etc and organic acids such as citrate, malate, oxalate, amino acids, benzoic acids, phenol, etc in a process called rhizodeposition (Chang et al., 2013; Geng et al., 2017; Zhang et al., 2018). Excreted sugars act as a carbon source for microbes and excreted vitamins stimulate microbial growth. Organic pollutants present in the wastewater gets attached on the biofilm/biomass, while passing through the root mat and degrade biologically. Organic removal efficiency depends upon the rate of metabolism of bacteria, fungi and beneficial algae present in the biofilm (Chen et al., 2012; Luca et al., 2019; Zhao et al., 2016). Degradation rate of organic matter depends upon the oxygen concentration in the water body. Plant root increases the dissolved oxygen concentration in water. Apart from this a lot of factors/processes contribute to deplete oxygen and these are; (1) Turbulence cannot be created in the water body by wind waves due to presence of floating plant, (2) Light cannot penetrate into the water body due to the presence of surface macrophyte restricting the growth of

photosynthetic algae, which prevents re-aeration process, (3) Respiration of aerobic bacteria in degradation process consumes the oxygen present in water (Di Luca et al., 2011; Song et al., 2014; Sun et al., 2009; Winston et al., 2013). Tanner and Headley (2011) reported lower dissolved oxygen in planted water body than unplanted one and justified that respiratory oxygen demand was higher than root oxygen release. In another study, Van De Moortel et al. (2010) and Wu et al. (2011) observed higher dissolved oxygen in planted unit than unplanted one. Billore et al. (2009) reported 40–50% BOD removal during the treatment of river water using *Phragmites karka.* Zhang et al. (2018) found 73.4–88.3% COD removal by planting *Canna indica* in a floating bed. In another experiment performed by Benvenuti et al. (2018), domestic sewage was treated using *Typha domingensis* and 55% COD removal was reported. Eutrophic pool water was purified using a lab scale circular reactor installing a floating bed of *Lolium* species and 66.8% COD removal was obtained (Li et al., 2011).

Suspended particles are either organic (bacteria, algae) or inorganic ($> 2\,\mu m$) in nature and if present in water, decreases light penetration. They are not directly taken up by plants or microorganisms (Lynch et al., 2015). Water flow promotes the removal of suspended solids in the root zone by filtration, so the removal of solids is higher in stormwater ponds than in stagnant lakes. Suspended solids are usually removed by sedimentation process and get deposited in the bottom zone from where it needs to be removed strategically (Kerr-Upal et al., 2000). Very less amount of solids get deposited on the biofilm and are digested by microbes (Cao and Zhang, 2014). Smith and Kalin (2000) reported 0.02 kg of solids trapped per m^2 of root surface area in a two year old floating *Typha* species planted in acid mine drainage pond. In a long term treatment process, entrapped solids in the roots will be sloughed and more surface area will be available for the attachment of solids. Table 2 shows the removal of organic and other pollutants in wastewater using various floating beds.

5.2. Nutrients (Nitrogen and Phosphorous)

Nitrogen removal mechanism in EFB systems are ammonification, ammonia volatilization, nitrification-denitrification, microbial assimilation, plant uptake, etc (Vymazal, 2007). Nitrogen transformation and removal mechanism in EFB is shown in Fig. S1. Usually nitrogen is present in the wastewater in four different forms i.e. Org.-N, NH_4^+-N, NO_2^-N and NO_3^-N (Gao et al., 2018). Nitrification-denitrification process is a dominant mechanism of nitrogen removal. It is a two step process: nitrification is an oxidation process in which ammonia is converted to nitrate and denitrification is a reduction process in which nitrate is reduced to N_2 gas and released to atmosphere (Pavlineri et al., 2017; Zhang et al., 2017). Organic nitrogen converts to NH_4^+-N through microbial conversion (ammonification) and NH_4^+-N may be volatilized or taken up by macrophyte roots. Ammonia volatilization is a physical removal process in which NH_4^+-N gas can be removed through mass transfer from the water surface to the atmosphere in alkaline condition.

Remaining NH_4^+-N oxidize to NO_3^-N by ammonium oxidizing bacteria (AOB) and nitrifying bacteria (*Nitrosomonas, Nitrosopira, Nitrosococcus,* etc) (Benvenuti et al., 2018; Qing et al., 2016). Oxidation takes place in the presence of oxygen, released by roots or by atmospheric oxygen transferred to the surface water. The bacterial community is nourished by plant roots. Bottom zone water of the water body contains less amount of oxygen as atmospheric oxygen could not get diffused to so deep. Anoxic environment is created in the bottom zone of the water body and denitrification occurs in this zone by denitrifying bacteria (*Bacillus, Neisseria, Pseudomonas,* etc) with NO_3^-N being converted to N_2 and N_2O (Chan et al., 2008; Weragoda et al., 2012; Williams et al., 2002). The intermediate form of nitrogen i.e. NO_2^-N and NO_3^-N is also taken up by bacteria, algae and plants and gets accumulated in their tissues. In this way the inorganic nitrogen present in water is converted to biomass, which can be permanently removed by the harvested plants. Sedimentation is also another method of nitrogen removal, but in this process nitrogen still remains in the water body and heavy wind or storm may bring all nitrogen back into water. According to Saunders and Kalff (2001) 80% of nitrogen is removed by denitrification and remaining 20% is removed by bio-accumulation and sedimentation process. Gao et al. (2018) removed 53.3–90.9% TN from river water using *Iris pseudacorus* floating bed. Similarly, Luca et al. (2019) informed about more than 90% NH_4^+ and NO_3^- removal with the help of *Typha domingensis.* Yang et al. (2008) observed 31–64% TN reduction in a nutrient solution by *Oenanthe javanica.* During aquaculture wastewater treatment Li and Li (2009) obtained TN removal of 30.6% using a floating bed of *Ipomoea aquatica.*

There are two forms of phosphorous present in the wastewater: organic phosphorus (Org.-P) and inorganic orthophosphate (PO_4^{3-}P). Organic phosphorous is converted to dissolved form or inorganic form by microbial action and assimilated in the plants and microorganisms (Sheng et al., 2013). Phosphorus uptake depends upon the types of vegetation, biomass growth rate, nutrient storage capacity, structure of the root and types of tissues present in the vegetation (Sun et al., 2009). According to Reddy and DeBusk (1987), if growth rate of plant is higher, phosphorous uptake capacity is also higher. In general, phosphorous is usually removed by adsorption, precipitation and complexation processes. Phosphorous present in the suspended form also settle in the bottom of the water body (Kyambadde et al., 2004; Zhang et al., 2018). Zhang et al. (2018) removed 50.9–74.0% TP from a simulated water using *Canna indica*. Benvenuti et al. (2018) reported about 37% TP removal from domestic wastewater using an EFB made up of *Typha domingensis.* Saeed et al. (2016) reported 23.4% TP removal from polluted river water installing an EFB consisting of *Phragmites australis* and *Canna indica.* In another experiment, Sheng et al. (2013) found 87.5% TP removal while treating river water using *Equisetum* and *Ipomoea* sp.

5.3. Heavy metals

Phytoremediation is a natural process of cleaning wastewater using green plants. Heavy metals present in wastewater are usually absorbed or up taken by the roots and translocated to the shoot, after which the plants are harvested and heavy metals are removed. Plants used in this remediation process should have high pollutant accumulation capacity, high growth rate, complex root network, quick adaptation process and high tolerance limit, etc (Anning et al., 2013; Bokhari et al., 2016; Saeed et al., 2016). Road runoff, commercial areas, domestic as well as industrial wastewater are some of the sources of heavy metals in surficial water. The common heavy metals present in the wastewater are As, Cr, Cu, Zn, Ni, Pb, etc (Kumari and Tripathi, 2015; Lu et al., 2011).

There are different stages of phytoremediation process like phytostabilization, phytodegradation, phytofiltration, phytoextraction, phytoaccumulation and phytovolatilization (Fig. 5). The first three stages occur within the media (soil, water, gravel, etc) and heavy metals get accumulated in the above ground biomass (Basile et al., 2012; Singh et al., 2010). Heavy metals uptake depends upon the type of aquatic plant species and pollutant level in the wastewater. In floating plants, when the root system comes in contact with the water, metals get absorbed in the roots and thereafter passive or active processes occur through cell membrane to translocate the heavy metals to the aerial parts. In order to have high absorption of metals, plants should have dense root system, high surface area, active surface microorganisms (Abdallah, 2012; Mukhopadhyay and Maiti, 2010; Sud et al., 2008).

According to Vymazal (2016) most plants that accumulate heavy metals do so in the underground tissues. Few species translocate metals to the green parts. Growth rate and metal concentration in the plant roots have direct impact on metal accumulation. Factors like water temperature, pH, salinity, redox potential and sun rays affect the plant growth and its accumulation capacity (Chaudhuri et al., 2014; Hasan et al., 2007). Heavy metals are present in the wastewater in particulate

Table 2
The use of Ecological floating bed for the treatment of various types of wastewater.

Sl. No.	Types of wastewater	Plant species	Organics removal (%)	Nutrient removal (%)	Dimension (L x W x H) (cm)	Operation period (days)	References
1	River water spiked with KNO_3 and NH_4Cl	*Iris pseudacorus*	–	TN 53.3–90.9%	85 × 40 x 90	3	Gao et al. (2018)
2	Pond water spiked with NH_4NO_3 and KH_2PO_4	*Typha domingensis*	–	TP > 90, NH_4^+ 96, NO_3^- > 90	Plastic reactor 70 L	Acclimatization 15, Operation 28	Luca et al. (2019)
3	Secondary effluent	*Cyperus papyrus* *Miscanthidium violaceum*	BOD 83.1, BOD 47.8	TN 66.8, NH_4 60.2, TP 61.8 TN 56, NH_4 47.1, TP 40.8	300 × 250 x 20 300 × 250 x 35	2.7	Kyambadde et al. (2004)
4	Lake water	*Ipomoea aquatica*	–	TN 66.4–76.5, NH_4 58.7–68.9, TP 45.7–61.7	100 × 100 x 110	–	Li et al. (2010)
5	River water	*Phragmites karka*	BOD 40-50	TN 45–50, NH_4 45-55	200 × 100 x 10	–	Billore et al. (2009)
6	Lake water	*Typha orientalis, Eleocharis dulcis, Juncus effuses*	SS 80	TN 66.6, PO_4 64, TP 74.4	Depth 165, Diameter 130	7	Lu et al. (2015)
7	Synthetic greywater	*Phragmites australis*	BOD 33.4, COD 27.2	PO_4^{3-}P 18.9	14-L plastic buckets	7	Abed et al. (2017)
8	Aquaculture wastewater	*Ipomoea aquatica*	–	TN 30.6, TP 18.2	200 × 300	–	Li and Li (2009)
9	Simulated wastewater	*Rumex japonicus, Oenanthe hookeri, Phalaris arundinacea, Reineckia carnea*	–	TP 74-98	43 × 32 x 7	10	Geng et al. (2017)
10	River water	*Equisetum* sp., *Ipomoea aquatica*	COD 79.3	NH_4 83.6, TP 87.5	–	–	Sheng et al. (2013)
11	Eutrophic water	*Iris pseudacorus*, *Canna indica*	COD 23.5–70.6	TN 29.8–49.3, NH_4^+-N 33.9–49.2, NO_3^--N 53.8–69.5	20 × 20 x 80	4	Qing et al. (2016)
12	Secondary effluent	*Iris pseudacorus*	–	TN 74.6–88.5, TN 59.9–89.4	60 × 38	3	Gao et al., 2017
13	Polluted river water	*Phragmites australis, Canna indica*	BOD 51.8, COD 40.8	NH_4^+-N 44.2, NO_3^--N 30.2, TP 23.4	300 × 58	–	Saeed et al. (2016)
14	Domestic sewage	*Typha domingensis*	BOD 56, COD 55, TSS 78	TKN 41, TP 37	1700 × 1700 x 250	11.5	Benvenuti et al. (2018)
15	Simulated wastewater	*Canna indica*	COD 73.4–88.3	TN 80.7–47.0, NO_3^--N 82.8–98.1, NH_4^+-N 25.1–59.4, TP 50.9–74.0	60 × 40 x 4	–	Zhang et al. (2018)
16	Domestic wastewater	*Typha angustifolia*, *Canna iridiflora*	BOD 48.5–76.1 BOD 63.5–85	NH_4 50–86.4 NH_4 58.4–81.6	100 × 50 x 65	12–14	Weragoda et al. (2012)
17	Eutrophic pool water	*Lolium perenne*	COD 66.8	TN 55.6, NH_4 62.8, TP 87.1	Diameter 80, Height 100	–	Li et al. (2011)
18	Nutrient solution	*Oenanthe javanica*	COD 17-43	TN 31–64, TP 8-15	200 × 100 x 75	1–3	Yang et al. (2008)

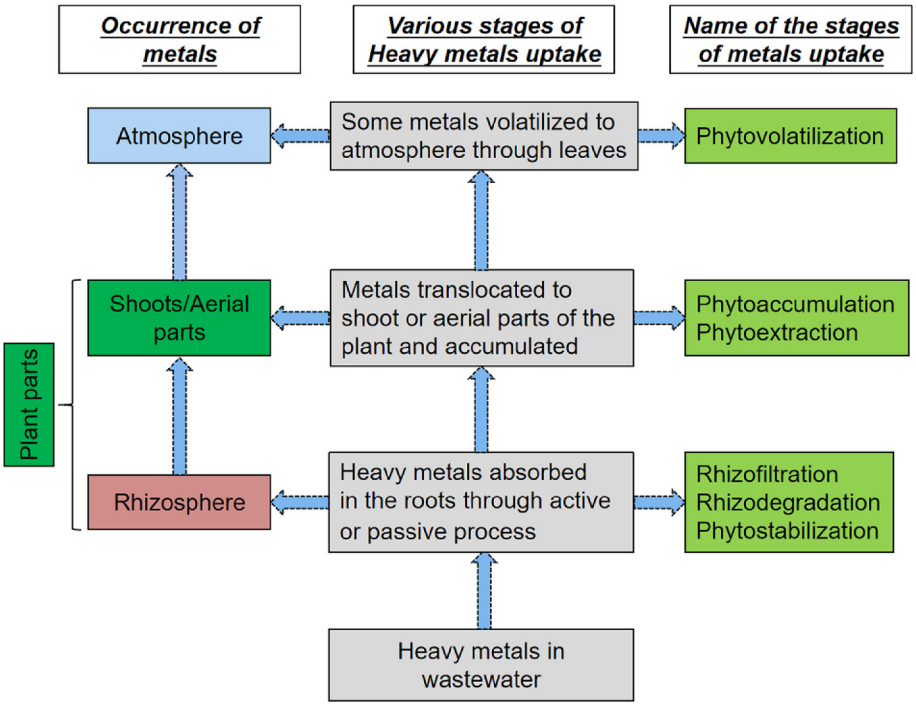


Fig. 5. Different phytoremediation processes for heavy metal removal.

as well as dissolved form. Particulate metals are trapped in the rhizosphere and the biofilm, whereas dissolved metals gets directly absorbed by the plants (Dhir et al., 2008; Lima et al., 2013). Various heavy metals mechanisms are shown in Fig. S2.

Adsorption and translocation of heavy metals is called bioaccumulation potential which is dependent on various biotic and abiotic factors. Rhizofiltration potential (RP) is the total heavy metals absorbed from wastewater (mg $_{\text{heavy metal}}$ m^{-2} $year^{-1}$) and can be calculated using following equation (Neugschwandtner et al., 2008):

$$RP = \left(\frac{C_{leaves}{}^{*}M_{leaves}}{M_{total}} + \frac{C_{roots}{}^{*}M_{roots}}{M_{total}}\right)^{*}M_{plant} \quad (1)$$

where.

M_{leaves} = Leaf dry biomass yield (g)
C_{leaves} = Concentration of heavy metal in leaves (μg/g)
M_{leaves} = Leaves dry biomass yield (g)
C_{roots} = Concentration of heavy metal in roots (μg/g)
M_{roots} = Roots dry biomass yield (g)
M_{total} = Total (leaves and roots) dry biomass yield (g)
M_{plant} = Mean of plant yield (g dry weight m^{-2} $year^{-1}$)

The total uptake capacity of the metals by a plant is called bioconcentration factor (BCF) (Massa et al., 2010). It is represented as:

$$\text{Bioconcentration factor (BCF)} = \frac{\text{Metal concentration in plant}}{\text{Metal concentration in water}} \quad (2)$$

Translocation of heavy metals from the root and rhizomes to the stem or leaves is called translocation factor (TF) (Fawzy et al., 2012). It is represented as:

$$\text{Translocation factor (TF)} = \frac{\text{Element concentration in plant}}{\text{Element concentration in water}} \quad (3)$$

The common used aquatic plant in floating bed for the heavy metals removal are *Eichhornia crassipes, Pistia stratiotes, Lemna minor, Salvinia* species. Table 3 shows various aquatic plants used in the floating bed design and their heavy metals removal capacity. Duck weed (*Lemna minor*) is the fastest growing flowering plant and can hold up to a wide range of temperature (10-35^{O}C) and pH (3–10) (Lu et al., 2011). According to the reports available, *Lemna minor* can store various heavy metals like Cd, Zn, Ni, Cu, B, Mn, As, etc (Bokhari et al., 2016; Sud et al., 2008). Miretzky et al. (2006) reported that dried *Lemna minor* also removes Cd, Zn and Cu from polluted water. Hua et al. (2012) reported significant amount of Mn removal using water lettuce (*Pistia stratiotes*). Lu et al. (2011) mentioned that major portion of the metals remain in the roots rather than transferring to shoot.

Mishra et al. (2009) observed 80% Hg removal in a coal mining wastewater containing 2–10 μg/L of Hg. Water hyacinth (*Eichhornia crassipes*) is also a dominant aquatic vascular plant. Hasan et al. (2007) stated that *E. crassipes* can survive extreme conditions and uptake high concentration of heavy metals. The order of metal storage in water hyacinth is leaves < stems < roots (Kay et al., 1984). Miretzky et al. (2006) informed that dry powder of water hyacinth can adsorb heavy metals in a cost effective way. Roots of *Salvinia* species store high amount of heavy metals than its leaves (Dhir et al., 2008). As indicated by Prado et al. (2010), high amount of Cr is accumulated in submerged leaves of *Salviana minima* than in floating leaves. To improve the performance of EFB, nowadays the above system is used in hybrid or integrated mode with other systems also. Some examples of hybrid EFB and their advantages and disadvantages are described in Table S2 and Table S3. Apart from this performance of various biological system for treatment of different types of wastewater are also shown in Table S4.

6. EFB in low temperature areas

In EFB, various pollutants removal processes are influenced by temperature. Physiology of floating plant governed by solar radiation and temperature. Low temperature restrains microbial activities and reduces their growth resulting in low purification efficiency. TSS removal in EFB is mainly due to physical processes such as sedimentation, decantation and filtration, which are not strongly sensitive to season or temperature. Many previous studies on EFB suggest that TSS removal is mostly unaffected by cold condition. Smith et al. (2006) reported 95% TSS removal efficiency during treatment of dairy wastewater in Atlantic, Canada. Postila et al. (2015) observed 80% TSS removal during peat extraction in Finland. Similarly, Heyvaert et al. (2006)

Table 3
The use of Ecological floating bed for the treatment of heavy metals rich wastewater.

Sl. No.	Heavy metals	Plants	Conditions	Removal Efficiency (%)	References
1	Cd, Fe, Cr, Pb, Mn, Cu, Ni, Zn	*Typha angustifolia, Limnocharis flava*	Wastewater in oxidation pond	Ni 74.87, Cd 61.07, Pb 62.07, Cr 69.17, Zn 63, Cu 79.07, Fe 81.17, Mn 68	Saeed et al. (2016)
2	Cd, Pb	*Lemna gibba*	Concentration of 2, 5 and 10 mg/L	Cd 41.6 (10 mg/L at pH 9) and 84.8 in (2 mg/L at pH 7); Pb 98.1 (10 mg/L at 7 pH) and 60.1 (2 mg/L at 9 pH)	Verma and Suthar (2015)
3	Cu, Zn, Cd, Cr, Pb, Ni, Fe	*Phragmites australis, Typha latifolia*	Mixture of sewage and industrial effluents	Fe 80.1 ± 0.3, Cd 60 ± 1.2, Cu 78 ± 1.2, Pb 61.0 ± 1.2, Zn 61.0 ± 1.2, Ni 73.8 ± 0.6, Cr 68 ± 0.4	Kumari and Tripathi (2015)
4	Cr, Cd, Zn, Pb, Cu	*Lemna gibba*	Cr 0.1, Zn 1.25, Cd 1.5, Cu 0.05, Pb 0.25 (mg/L)	Zn 51–82, Cd 33, Cr 94, Pb 36, Cu 29	Sekomo et al. (2012a)
5	Hg, Cu, Fe, Zn, Pb	*Typha Latifolia*	River water	Pb 20.29, Fe 34.28, Hg 46.63, Zn 51.88, Cu 33.84	Anning et al. (2013)
		Limnocharis Flava, Thalia Geniculata,		Zn 44.45, Fe 77.09 Hg 51.61, Pb 11.62, Cu 4.21 Fe 45.04, Hg 45.04, Pb 30.26, Zn 41.58, Cu 9.39	
6	Zn, Cd, Cu, Pb	*Lemna minor*	Synthetic wastewater	Cd 95, Pb 93, Zn 81.2, Cu 86.5	Basile et al. (2012)
7	Cd, As	*Micranthemum Umbrosum*	As concentration 0–1 μg/mL and Cd concentration 0.3–30 μg/mL	Cd 60–73.1, As 79.3–89.5	Islam et al. (2013)
8	Cd	*Lemna minor*	Concentrations of, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 mg/L	42.0–78.0	Chaudhuri et al., 2014
9	Pb, Cu	*Pistia stratiotes*	Steel industry effluent	Pb 70.7, Cu 66.5	Aurangzeb et al. (2014)
10	Zn, Cu, Pb, Cd	*Eichhornia crassipes*		Pb 98, Cd 98, Zn 84, Cu 99	Sekomo et al. (2012b)
11	Cr, Zn	*Eichhornia crassipes*	Stock solutions	Cr 63 (day 3), 80 (day 9); Zn 67 (day 9), 96 (day 12), 100 (day 15)	Swarnalatha and Radhakrishnan (2015)
12	Pb, Cr	*Lemna gibba*	Concentration of 2, 4, 10 and 15 mg/L	Pb 91–96.4, Cr 86.2–94.8	Abdallah (2012)
13	Cr, Cu, Zn, Ni	*Salvinia molesta*	Initial concentration of 15 mg/L	Cr 41.4, Zn 84.8, Cu 73.8, Ni 56.8	Dhir et al. (2011)
14	Cr, Pb	*Ceratophyllum demersum*	Synthetic wastewater	Pb 92–95, Cr 13–84.3	Lima et al. (2013)

obtained 91.2% TSS removal during treatment of stormwater runoff using EFB. It has been well accepted that biological processes are temperature dependant and degradation of soluble organic matter in EFB is highly driven by biological activity, which may be reduced. However, there have been controversial opinions with respect to the temperature dependence in BOD_5/COD removal within floating bed wetlands. Thoren et al. (2004) obtained 52.2% BOD removal efficiency while treating agricultural runoff in Sweden, but Bosak et al. (2016) found 96% BOD removal during potato farm wastewater treatment in Ottawa, Canada. Major removal mechanisms for nitrogen is bacterial nitrification and denitrification. Nitrogen removal was largely dependent on microbial activity in root zones, thus the dependence of removal efficiency on temperature was much more significant. Vymazal (2005) stated that the optimum temperature for nitrification in pure cultures ranges from 25 to 35 °C. Ng and Gunaratne (2011) indicated that ammonia volatilization increases 1.3–3.5 times with each 10 °C rise in temperature from 0 to 30 °C, and denitrification rate almost double (1.5–2.0) with each 10 °C increment. Therefore, a low-temperature environment is unfavourable for bacterial proliferation and metabolism and microbial nitrification is restrained at low temperature. Postila et al. (2015) reported only 14% TN removal in a floating bed treatment process in Finland.

7. Biomass harvesting and maintenance

Continuous and slow addition of pollutants from different sources makes the water body contaminated permanently. If a water body is polluted, it means the rate of pollutant addition is more than its self purification (biological process) capacity. In ecological floating bed system, suitable local aquatic plant bed is installed in the polluted lake. The bed is usually made up of buoyancy materials to provide continuous upthrust to the plants and the surface area to support growth of microbes (Lynch et al., 2015; Xian et al., 2010). The chosen plant species usually have dense root system to remove pollutants effectively. Flowering plants add aesthetic value to the nature and provides habitat for various fauna. Local plants are chosen over others as they do not pose any risk of invasive if escaping from the water body (Headley and Tanner, 2012). A lot of floating plants like *Lemna* sp. and *Azolla* sp. have high phosphorous uptake capacity. Since the roots of the floating plants do not get attached to the bottom, so it can be harvested easily. It is highly recommended to harvest the floating plants in regular intervals (Hubbard et al., 2004; Yeh et al., 2015). The working principle and step by step processes of EFB is shown in Fig. 6.

According to Zhou and Wang (2010) plants need to be harvested before arrival of its decay phase, because once this phase is attained by the plants, nutrients stored in the leaf and other aerial parts start entering the water again. Researchers have reported that floating plants develop thinner roots to facilitate the maximum storage of nutrients in the root system (Cao and Zhang (2014); Gao et al., 2018; Zhang et al., 2017). Tanner and Headley (2011) stated that about half of the total nutrient uptake by the floating plants are stored in their roots. Wang et al. (2015) also concluded that harvesting only above the water portion will not remove all nutrients from water as significant amount of nutrients are accumulated in the below water biomass. Harvesting above water portion only prevents the plants from dying as new shoot grows from the cutting surface. So more research becomes necessary about the partial or whole plant harvesting. As discussed above, during the growing phase aerial tissues contain higher nutrient concentration and as they mature and senescence phase is reached, nutrients remobilize and translocate to the roots and rhizomes (Bi et al., 2019; Zhu et al., 2011).

Vymazal (1995) mentioned that 50% of the aerial nutrients get translocated to below water plant parts during senescence phase. After an extensive research Wang et al. (2015) concluded that above water biomass contains highest concentration of nutrients during summer, but at around September nutrients start to translocate to below water

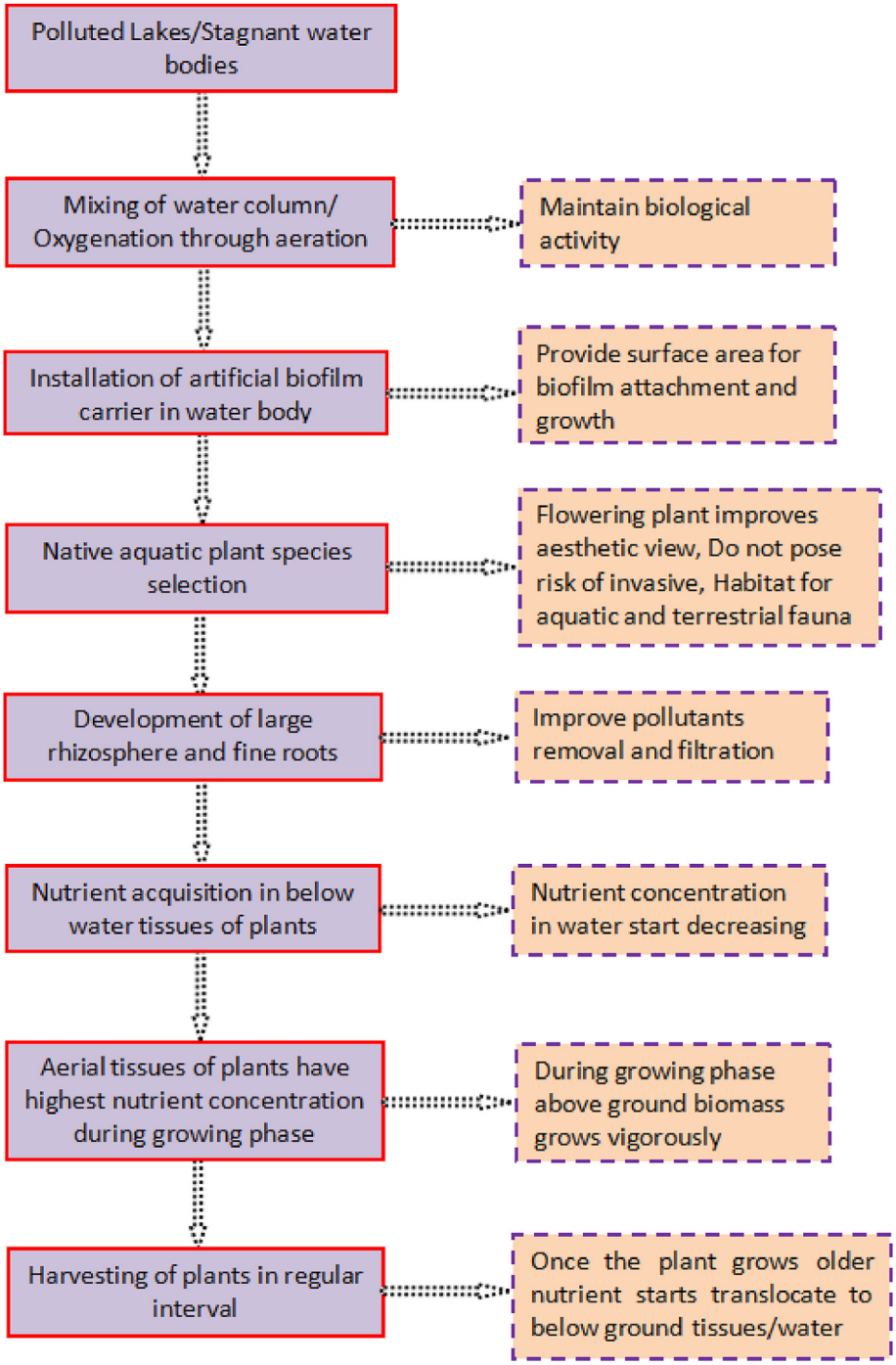


Fig. 6. Working principle of Ecological Floating Bed (EFB).

biomass. Meuleman et al. (2002) reported that TN removal efficiency is increased from 9% to 20% and TP removal efficiency is increased from 6% to 25% when harvesting of the above water tissues was done is September.

Harvested biomass can be used as animal food directly. Apart from this harvested plants can be processed by composting and vermi-composting (Brisson and Chazarenc, 2009; Islam et al., 2013) (Fig. S3). First the harvested plants are fragmented or chopped to the size of 2–3 cm. Since the aquatic plants contain a lot of water, it needs to be dried. After that bulking agents (cow dung, sludge, saw dust) are added to the biomass to initiate composting process (Meuleman et al., 2002). In semi-decomposed substances, earthworm are added to accelerate the composting process. The final product obtained is called vermicompost and it can be utilized as soil amendment or directly as fertilizer in agricultural land (Borne, 2014). The plants accumulating heavy metals can be burnt and from the generated ash heavy metals can be extracted. As time progresses, sediments get accumulated in the bottom and after years it needs to be removed as it may contain high concentration of metals and other contaminants. Redox conditions of the sediments determine the mobility of the metals in a particular way for each metal.

Changes in temperature affect the microbial activity. During summer season high microbial activity is observed while during winter season activity is low (Bu and Xu, 2013). So, it can be concluded that season and climate have major impact on the performance of ecological floating bed. It is always necessary to keep an eye on the maintenance of floating bed for effective removal of pollutants. Harvesting needs to

be done at proper time.

8. Future research

- ✓ In EFB phosphorous is usually removed by sedimentation or plant uptake. Major fraction of phosphorous can also be removed by adding adsorbent materials like laterite, zeolite and vermiculites in the substratum. Future research needs to be focused on addition of phosphorous absorbing materials in the water body to enhance phosphorous removal, which should not affect the physical characteristics of water.
- ✓ Investigation is necessary to establish a relationship between water depth and rooting depth of the aquatic plants. Water depth is a major factor as it affects the aeration, sun light penetration to the water body and to prevent the roots from attaching to the sediments.
- ✓ It is necessary to continuously check the performance of EFB with different macrophyte coverage ratio. Factors like water depth, retention time and coverage ratio needs to be optimized while designing an EFB and their interaction effect also needs to be studied.
- ✓ Redox status of underlying water and sediments required to be monitored to evaluate how these conditions impact pollutant removal process. Changing redox condition in the water affect nutrients and metals mobilization in it. Root growth of a macrophyte in varying redox and nutrient conditions needs to be investigated.
- ✓ There is a need to focus on the quantification of amount of fine organics and associated metals captured within the root biofilm network beneath an EFB and the rate at which these materials may be sloughed off and deposited within the sediments.
- ✓ While designing a stagnant floating wetland, it is necessary to focus on the prevention of formation of dead zones and short-circuits in the water body. The hydraulic issues can partially be solved by proper utilization of wind waves to aerate water.
- ✓ Very few researches have been done related to pathogen (Total coliform, Fecal coliform) removal in EFB, which can be explored.
- ✓ Dissolved oxygen is necessary for organic degradation and nitrification process. Minimum 4 mg/L of dissolved oxygen is required to sustain aquatic life. Rather than use of mechanical aerator, natural process like algal photosynthesis mechanism can be used and research is necessary to implement this process (algal photosynthesis) in EFB.
- ✓ Due to climate change, water and air temperature increases and rainfall intensity also changes. It has direct impact on dissolved oxygen concentration, lake stratification, water level, salinity and pH of the water body. While designing EFB, climate change factor needs to be considered.

9. Conclusions

The available literature proves that Ecological Floating Bed (EFB) is one of the sustainable and eco-friendly green technology for the treatment of various types of wastewater. Different helophytes are used for the design of EFB and these types of plants have plenty of aerenchyma tissues to transfer oxygen from the above ground biomass to below ground biomass. Since the plant bed needs to be in floating condition, various buoyant materials like PVC pipes, polystyrene sheets, bamboo and various floating patent products are used to design the raft for providing sufficient buoyancy to the bed. Water depth and plant coverage ratio is a major factor while designing a floating wetland as it affects the atmospheric oxygen diffusion to the water body. Apart from the above factors, types of macrophyte species, biofilm and growth media also affects pollutant removal process. Organics and suspended solids are usually removed by filtration and aerobic degradation process. Nitrogen is majorly removed by nitrification-denitrification and plant uptake. Maximum fraction of phosphorous and heavy metals were removed by sedimentation and some amount by the plant uptake. Regular harvesting of plants is necessary to prevent translocation of nutrients from stem and leaves to the water.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.109550.

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